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Probability of Interference between LP-LDC and LBT MICS Implants in a Medical Care Facility

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***Abstract*—The latest generation of medical implants incorporate RF telemetry to facilitate communication of patient data to the patient's physician. Regulatory agencies have enabled medical implant telemetry by allocating RF spectrum in the 402-405 MHz band. The first generation of regulations mandated the use of a Listen-Before-Talk (LBT) protocol. Most of these regulators, recognizing the need for expanded services, are modifying the regulations to allow a Low-Power Low-Duty-Cycle (LP-LDC) protocol as an alternative access method.**

Medical implant device manufacturers incorporate mitigation techniques to maintain communication in the face of expected link impairments. Designers must understand the expected operational environment and probability of interference in order to incorporate appropriate levels of such mitigation techniques.

In this study the authors use the SEAMCAT-3 modeling tool to examine the probability of interference between LP-LDC and LBT medical implants in a medical care facility, where a high density of implants using either protocol can be expected. This study shows that because LP-LDC transmitters operate with very low power and low duty cycle, they can safely coexist with LBT devices, with extremely low probability of interference. Furthermore, with appropriate mitigation techniques, the probability of any harmful interference is virtually non-existent.

I. INTRODUCTION

A new frontier has been reached in medical implant device operation that enables home monitoring of a patient's medical condition. Employing embedded RF telemetry systems that operate in the 402-405 MHz Medical Implant Communications Service (MICS) band, medical implants can send reports to the patient's physician on a regular basis (see Fig. 1). This technology enables the physician to monitor the patient's medical condition, as well as the implant status, and receive reports of medical problems which would otherwise go undetected until the patient's next scheduled office visit.

In home monitoring systems, the implant uses extremely low power RF telemetry to communicate with a nearby transceiver, typically placed by the patient's bedside at home. The transmissions can take place without any actions required on the part of the patient. The transceiver relays the medical data from the implant to a service center via a built-in GSM wireless link or the patient's telephone landline. Transceivers with built-in GSM wireless modems are portable and can also be worn on the patient's belt to relay urgent medical events that may occur when the patient is ambulatory.

Fig. 1. Pacemaker and ICD using LP-LDC RF telemetry.

Because implant telemetry sessions in a physician's office could last for several minutes, regulators required that the devices use a bidirectional Listen-Before-Talk (LBT) protocol to mitigate the potential for interference to other MICS sessions. Although LBT techniques are well suited for mitigating interference during lengthy sessions in a medical facility, it is not necessarily the best choice for implants employing RF telemetry intended for home monitoring applications. LBT devices typically employ frequency-agile RF transceivers and the circuitry required to implement the protocol can consume a significant amount of power from the implant's battery. In a home monitoring use case, the implant transmits a relatively small amount of data on a daily basis. Although each RF transmission is brief and consumes very little power, the aggregate drain on the battery over the service life of the implant, which is expected to be seven years or more, can be very significant if the LBT protocol is implemented. In this case most of the power consumed in an LBT session occurs while performing a clear channel assessment and synchronizing the implant with the external transceiver, and is not due to the transmission of patient data.

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Designers of medical implants such as pacemakers and implantable cardioverter defibrillators (ICDs) must bear in mind that the telemedicine features remain of secondary importance when compared to the main function of the implant – regulating a patient's heartbeat and/or providing a life-saving shock to treat ventricular fibrillation. As such, careful consideration must be given to the design of the RF telemetry system to ensure it has minimal impact on device longevity. Because patients must undergo a surgical procedure to replace the implant when its battery is nearly depleted, designers must strive to eliminate all non-essential power consumption.

Most regulatory agencies that have adopted MICS are considering proposals to permit implant manufacturers the choice of implementing either the LBT protocol or a Low-Power Low-Duty-Cycle (LP-LDC) method. Both of these access methods are designed to mitigate interference, but the manner in which they do so is distinctly different. Devices employing the LBT protocol mitigate interference by performing a clear channel assessment prior to transmitting to determine which channels are unoccupied. Alternatively, they can select the least-interfered channel. LP-LDC devices mitigate interference by transmitting at very low power levels and limiting the duration of the RF transmissions to a very small duty cycle. Proposed regulations restrict LP-LDC devices to operating on one specific frequency in the MICS band. Examples of MICS regulations can be found at [1]-[5].

As noted above, the low power consumption of the LP-LDC approach makes it an attractive choice for medical implants with home monitoring requirements. Implants can also use LP-LDC as a beacon to initiate an LBT session. In a clinical setting, where many LP-LDC devices may be in close proximity to LBT devices, the potential for RF interference needs to be understood. A search of literature in the public domain indicates little has been done to investigate the probability of interference between LBT and LP-LDC devices. This study was undertaken in an attempt to quantify the potential for such interference in a medical care facility.

II. Methodology

In this study, two scenarios within a medical care facility are modeled to assess the probability of interference. Medical care facilities are most likely to have large numbers of implanted devices in close proximity, yielding higher levels of potential interference.

The first scenario analyzes the probability of telemetry transmissions from multiple patients with LP-LDC implants in a waiting room interfering with a MICS LBT session in an adjacent physician's office. The probability of interference is computed for up to one hundred patients with LP-LDC implants.

The second scenario analyzes the probability of one LBT telemetry session in a physician's office interfering with another LBT session in an adjacent physician's office. Analyzing this scenario provides a benchmark for comparing the relative potential for interference from LP-LDC devices.

The physical layout of a medical care facility is modeled, and the predicted RF signal levels between the implants and the physicians' programmers is analyzed using the Spectrum Engineering Advanced Monte Carlo Analysis Tool (SEAMCAT Version 3) developed by the European Radiocommunications Office [6]. Since no two medical facilities or physician's offices are the same, assumptions were made regarding their physical layouts. These layouts were based upon "typical" arrangements the authors have experienced in a clinical setting. These physical models are described in detail in their respective sections. Naturally, different physical models will result in different probabilities of interference, but large differences are not expected for other realistic models.

III. Probability of Interference and Link Reliability

The carrier-to-interference ratio (C/I) is used as a parameter to assess the potential for interference to an LBT MICS telemetry session. Since the actual C/I ratio necessary for a reliable link will vary as a function of modulation technique and system implementation, the study investigated the sensitivity of the link with this parameter as a variable. Using the C/I ratio as a system variable permits designers to gauge the link reliability of their specific system and not restrict the study to a particular implementation. By noting the dependence of the bit error rate on the C/I ratio, designers can assess the influence of error detection and correction techniques for their specific system.

In this study, SEAMCAT simulated one million Monte Carlo trials of different combinations of locations and propagation parameters, and computed the C/I for each trial. If C/I is too low in any trial, interference is assumed to occur. The probability of interference is reported as the fraction of the one 1 million trials with C/I too low.

The LP-LDC simulations were performed with duty cycles of 100%. This ensures all transmitters are active and transmitting during each trial. Since this study concerns transmitters with much lower duty cycles, the probability reported by SEAMCAT requires adjustments as further described for each scenario.

IV. Simulation Parameters

The general parameters used in all of the simulations are listed in Table I. Other parameters specific to the simulations are noted in their respective sections.

Proposed MICS regulations limit LP-LDC implant transmitters to 100 nW Effective Isotropic Radiated Power (EIRP). LBT devices can operate with up to 25 μW EIRP, but implanted devices commonly operate at reduced power levels (100 nW to 1 μW) to conserve battery power. Simulations are performed at both LBT implant power levels to gauge this parameter's effect on interference.

TABLE I SIMULATION PARAMETERS

Simulation Parameter	Value
LP-LDC Transmit Power	100 nW
LP-LDC Duty Cycle	0.01%
LBT Transmit Power	100 nW and 1 μW
Physician's Prog. Transmit Power	25 μW
Number of Interferers	1 to 20
Antenna Gains	0 dBi
Antenna Pattern	Omni-directional
Antenna Height	0.75 meters
Receiver Sensitivity	-105 dBm
Channel Bandwidth	300 kHz
LBT Monitoring System Threshold	-95 dBm
MICS channels	10
Indoor Wall Loss	5 dB
Indoor Wall Loss Std. Dev.	10 dB
Carrier-to-Interference (C/I)	14, 17, and 20 dB
Indoor Path Loss Model	Extended Hata - SRD

Physician's programmers normally operate at maximum EIRP since the programmer-to-implant communications link must overcome additional losses due to body tissue (implant EIRP is measured outside the body and thus includes the effect of tissue RF attenuation). The antennas are assumed to be omni-directional, and the antenna factors are included in the EIRP.

The maximum channel bandwidth allowed by regulation, 300 kHz, is used. The LBT devices are modeled to permit operation on ten equally spaced channels with a uniform probability distribution. The LBT Monitoring System Threshold, the criteria by which a MICS channel is deemed to be available, is based on FCC and ETSI regulations for a 300 kHz channel bandwidth.

The Extended Hata-SRD path loss model is used since it is the most applicable model in SEAMCAT for the indoor scenarios.

Other parameters are typical for MICS devices.

V. INTERFERENCE SCENARIO 1: LP-LDC PATIENTS IN A WAITING ROOM ADJACENT TO A PHYSICIAN'S OFFICE

One scenario for interference between LP-LDC and LBT devices occurs when numerous patients with LP-LDC implants are in a waiting room adjacent to a physician's office. SEAMCAT analyzed the potential for interference to an LBT session in a physician's office for up to one hundred patients with LP-LDC implants in a nearby waiting room. The situation, as modeled, is shown in Fig. 2.

The distance between the patient and the programmer in the physician's office is randomly varied from 0.4 to 2.0 meters. It is assumed the implant is transmitting data to the physician's programmer since its lower transmission power offers the greatest opportunity for interference to the link.

The distance between LP-LDC patients in the waiting room and the physician's programmer in the adjacent office is randomly varied from 2 to 8.5 meters. This scenario model also includes path losses due to one interior wall.

It is desired to find the probability of interference to a single LBT packet from the LP-LDC transmitters.

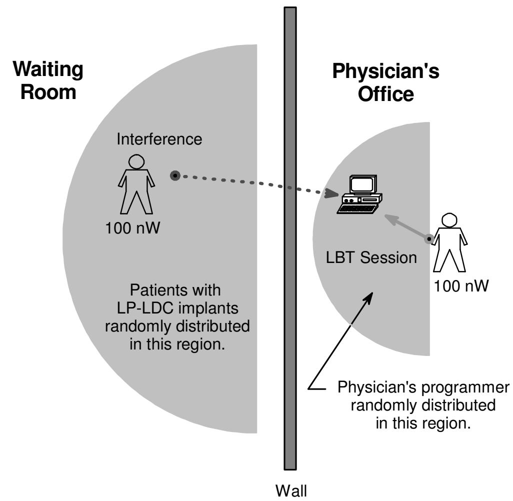

Fig. 2. LP-LDC implants adjacent to a MICS LBT session.

For a single interferer, a C/I of 14 dB, and all devices operating at 100% duty cycle, SEAMCAT found a probability of interference (P) of 2.83%. Since an LP-LDC transmitter can have a maximum duty cycle of 0.01% on a per-hour basis, the device is assumed to transmit for 0.36 seconds once per hour. Assuming a packet length of 100ms for the LBT implant data, and assuming the LBT implant's packet start time is uniformly distributed over an hour (3600 seconds), the single packet duty cycle is 0.0000277.

Computing the probability of a LP-LDC transmission interfering with a packet of the LBT session, the probability of two transmitters colliding can be found by considering the joint probability distribution of the two independent random transmission start times. Assume the first transmitter has a duty cycle of δ1 (expressed as a fraction) and further assume that the transmission starting time of this transmitter is uniformly distributed from 0 to (1- δ1)*1hour. Similarly, consider the starting time of the second transmitter, with a duty cycle of δ2, to be uniformly distributed from 0 to (1-δ2)*1hour. The probability of collision is found by making a two dimensional plot of the two starting times and noting the area when the starting time of the first transmitter is less than δ1*1hour before the starting time of the second transmitter and the area when the starting time of the second transmitter is less than δ2*1hour before the starting time of the first transmitter. This is shown in Fig. 3. The probability of collision is taken as the sum of these two collision areas divided by the total area. The probability of collision ($Pcoll$) becomes:

$$Pcoll = \frac{(\delta 1 + \delta 2) * (1 - (\delta 1 + \delta 2))}{(1 - \delta 1) * (1 - \delta 2)} . \quad (1)$$

For δ1=0.0001 and δ2= 0.0000277, the probability of collision becomes 0.0128%. Applying the probability of collision to the probability of interference, there is a 0.00036% probability of a single LP-LDC transmitter interfering with a given LBT packet in an adjacent office.

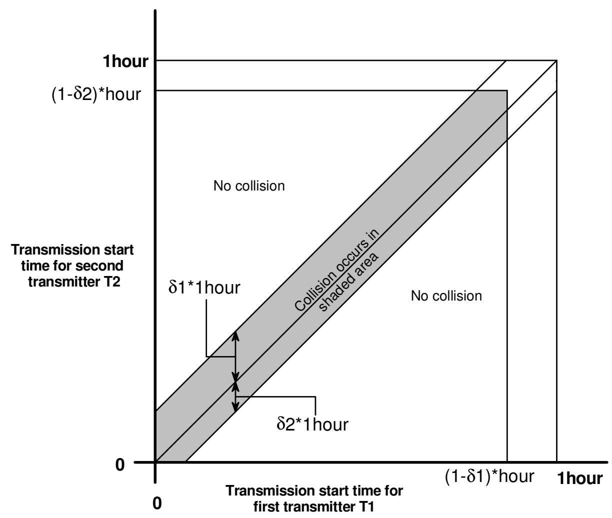

Fig. 3. Joint probability distribution for probability of collision.

If there are n LP-LDC transmitters, then the probability of interference is:

$$P(n) = 1 - (1 - Pcoll * P)^n \text{.} \tag{2}$$

The resultant probability of interference to the MICS LBT session as a function of the number of LP-LDC implants is shown in Fig. 4. For a C/I ratio of 14 dB, the probability of interference from ten LP-LDC transmitters in the waiting room is 0.00362%. This level drops below 0.00153% if the LBT implant transmits at 1 μW. One hundred 100 nW LP-LDC transmitters in the waiting room result in a probability of interference of 0.0362%. Other curves indicate the probability of interference if the LBT receiver requires a C/I ratio of 17 dB or 20 dB. Five 100 nW transmitters in the waiting room, perhaps a more realistic scenario, results in a probability of interference of approximately 0.00181%.

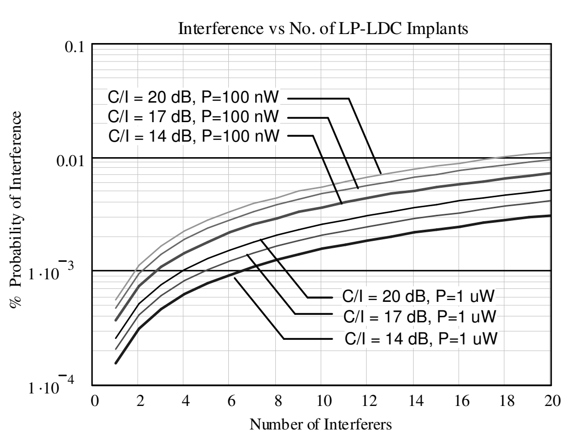

Fig. 4. Interference from LP-LDC implants to a MICS LBT session.

VI. Interference Scenario 2: LBT Sessions in Adjacent Physicians' Offices

The MICS protocol was designed to mitigate interference, but as demonstrated below, LBT-to-LBT interference can still occur. Consider a "hidden node" scenario in which two physicians in adjacent offices are performing patient examinations. While one physician is downloading data from an implant, it is possible that a second programmer that is performing a clear channel assessment in an adjacent physician's office will not see the first implant's RF transmissions. This second programmer may then select the same RF channel as the one already in use, which will result in co-channel interference.

Whereas LBT physician's programmers typically transmit near the maximum regulatory limit of 25μW, implant transmitters typically operate at approximately 100 nW to maximize implant longevity. When transmitting at this power level, the implant's radiated field strength in an adjacent physician's office can be less than the MICS monitoring system threshold power. When the programmer in the second office transmits on the same RF channel used in the first (adjacent) office, it could overpower and interfere with the weaker signal from the first implant.

Fig. 5 shows the situation for modeling two LBT sessions operating in adjacent physician's offices. In the simulation, the physicians' programmers are randomly distributed within 2 meters of the patient. The neighboring LBT devices can be as close as 1 meter in separation, with one interior wall separating the two offices.

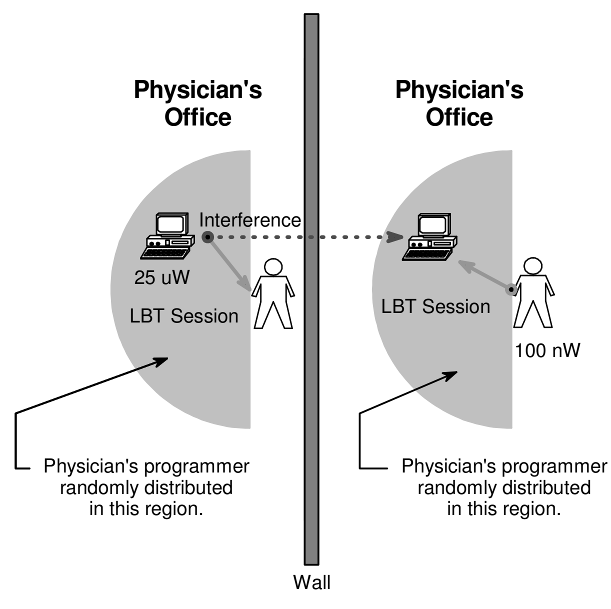

Fig. 5. Interference between LBT devices in adjacent physician's offices.

When a physician's programmer is transmitting, a programmer performing a clear channel assessment in an adjacent office will always detect its presence. However, as shown in Fig. 6, the simulation predicts that when the implant is transmitting, there is a 9.7% chance the implant signal level in the adjacent office will be below the MICS monitoring system threshold of -95 dBm; the clear channel assessment will then report the channel as available for use.

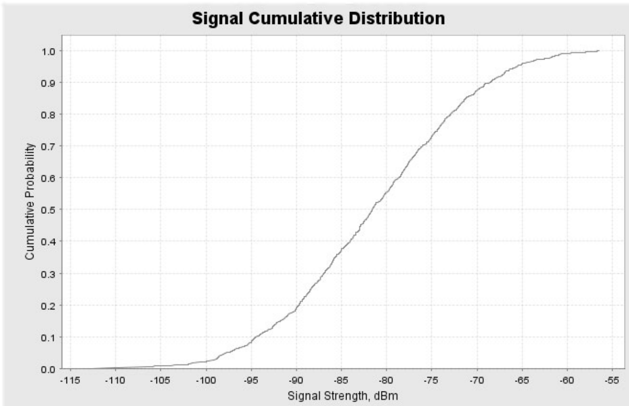

Fig. 6. Implant signal level in adjacent physician's office.

The LBT implant is assumed to be transmitting at a 50% duty cycle with transmission packet lengths of 100 ms. Assuming both LBT sessions have durations of five minutes and the duration of each follow-up examination is fifteen minutes, the session duty cycle is 0.333. The probability of not detecting an RF telemetry session in the adjacent office when performing a clear channel assessment is:

$$P_{not\_detecting} = P_{no\_TX} + P_{implant\_TX\_below\_threshold} \quad (3)$$

$$P_{not\_detecting} = (1-0.333)+(0.333)*(0.5)*(0.097)$$

$$P_{not\_detecting} = 0.6828$$

If the session in the adjacent office is not seen, the clear channel assessment results in a channel being chosen at random. Since there are ten channels, the probability of choosing the same channel as the adjacent office is 0.06828.

The interfering transmitter duty cycle is 50% of 0.333, but because the session packets are interleaved and the packet lengths are assumed to be the same length, the probability of collision *Pcoll* remains 0.333, or 33.3%. That is, if the interfering programmer transmits any time during the five-minute session it will collide with a data packet. Any collision will result in interference since the physician's programmer in the adjacent office transmits at a power level 24 dB greater than the implant.

The resulting probability that an LBT session packet will be interfered with is equal to 100%*6.828%*33.3%, or 2.28%.

VII. PERFORMANCE

Fig. 7 summarizes the results of the study for the analyzed scenarios. There is a greater probability of interference (2.28%) to a single LBT packet from an LBT session in an adjacent physician's office than from multiple LP-LDC implants in an adjacent room. One LP-LDC implant patient in a waiting room adjacent to a physician's office has a 0.000362% probability of interfering with an LBT packet. Ten LP-LDC transmitters in the adjacent waiting room results in a probability of 0.0036%, two orders of magnitude less than the probability of interference due to an LBT session in an adjacent physician's office.

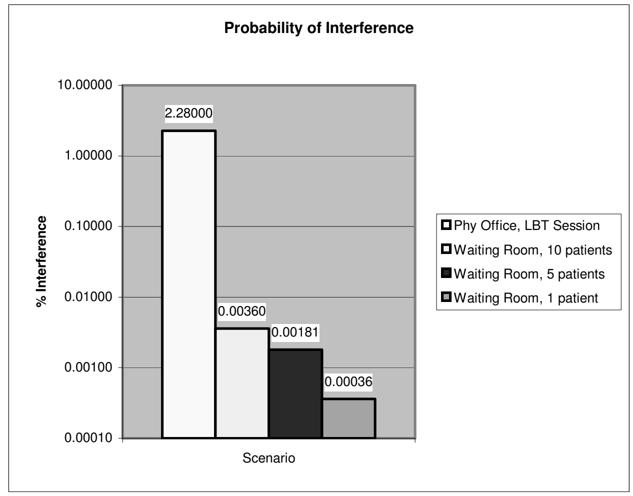

Fig. 7. Probabilities of Interference for LP-LDC and LBT devices.

VIII. CONCLUSIONS

The probability of interference to MICS LBT medical telemetry systems by a high density of LP-LDC implants is very small, and well within acceptable limits. In fact, the interference levels are less than the level expected between existing LBT systems. In addition to their low probability of causing interference, LP-LDC systems are ideally suited to home monitoring applications where daily telemetry sessions demand simple, low-power, energy efficient RF transmitters. Furthermore, LP-LDC offers a technique to simplify the initiation of a LBT session by providing a beacon signal that can serve to quickly synchronize the implant and external RF device. Even though LP-LDC transmitters operate on a single frequency in the MICS band, they can coexist with LBT devices due to their low power and low duty cycle.

REFERENCES

[1] FCC 99-363 MICS Report and Order
[2] FCC Notice of Proposed Rulemaking, RM-11271
[3] ETSI 301 839 –1 v1.2.1 (2006-05), Ultra Low Power Active Medical Implants and Peripherals operating in the frequency range 402 MHz to 405 MHz; Part 1: Technical characteristics and test methods.
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